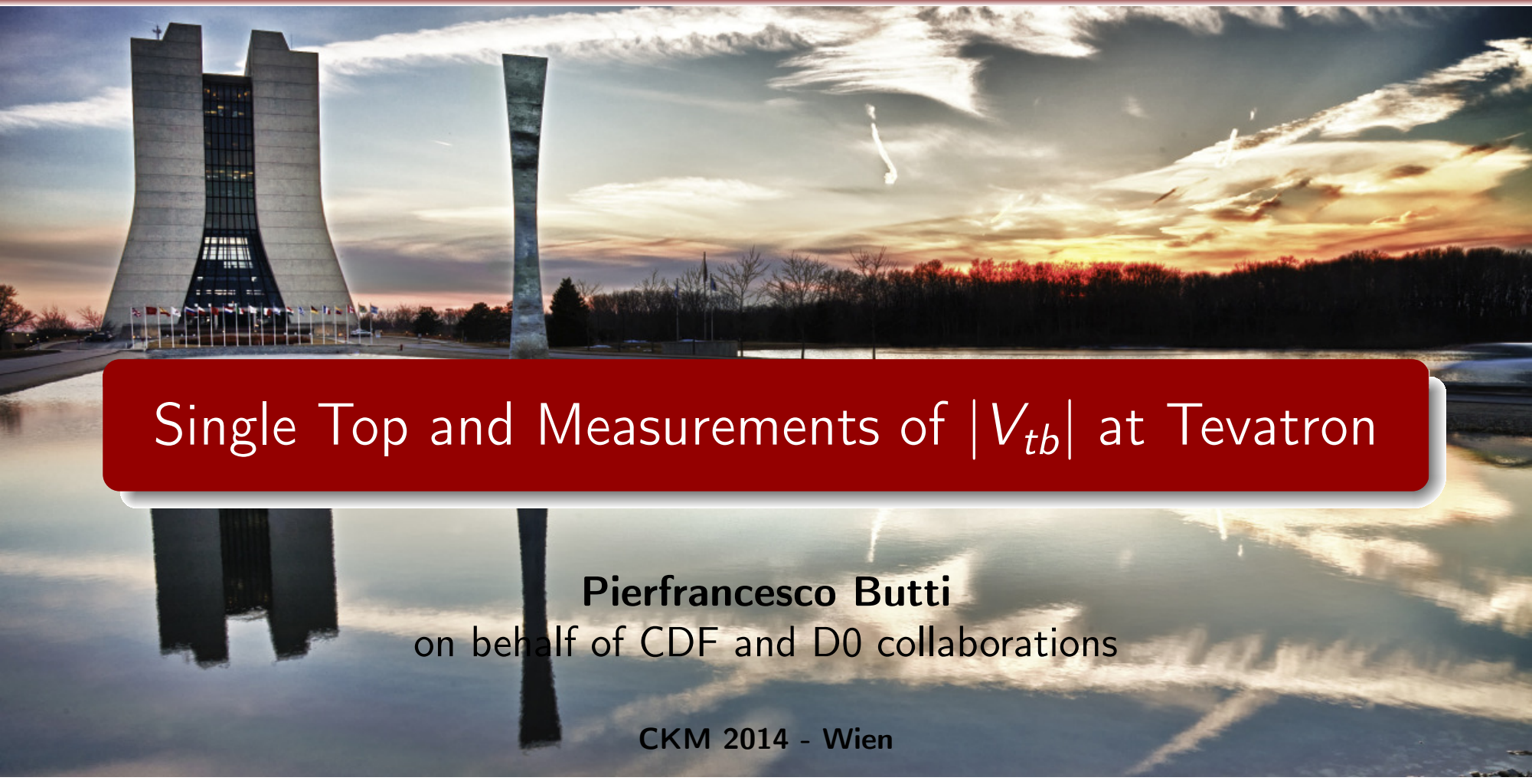


Single Top and Measurements of $|V_{tb}|$ at Tevatron

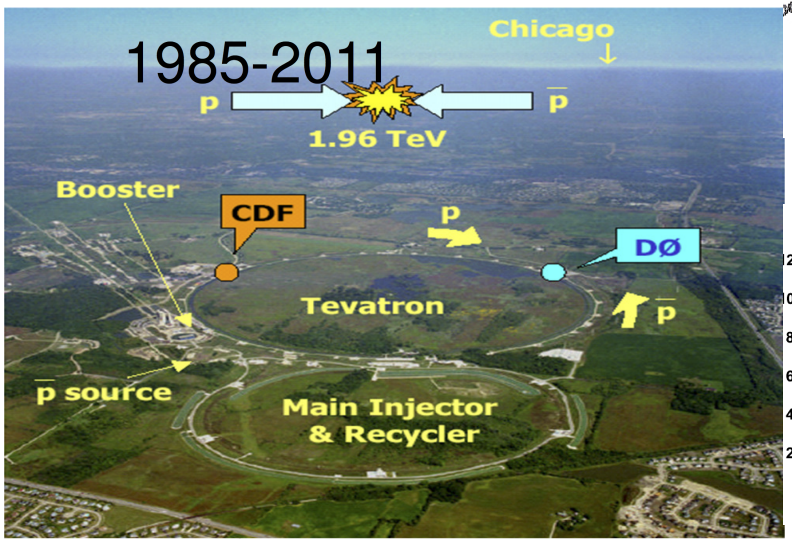
Pierfrancesco Butti
on behalf of CDF and D0 collaborations

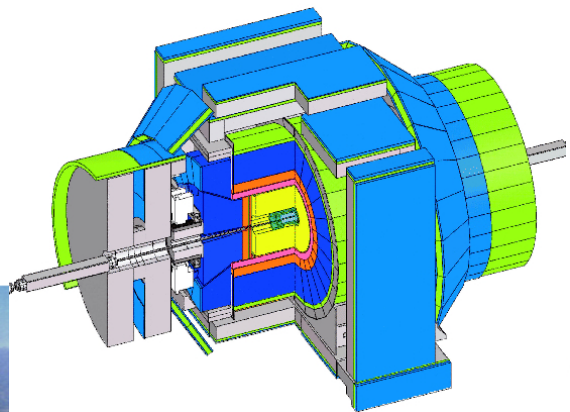
CKM 2014 - Wien

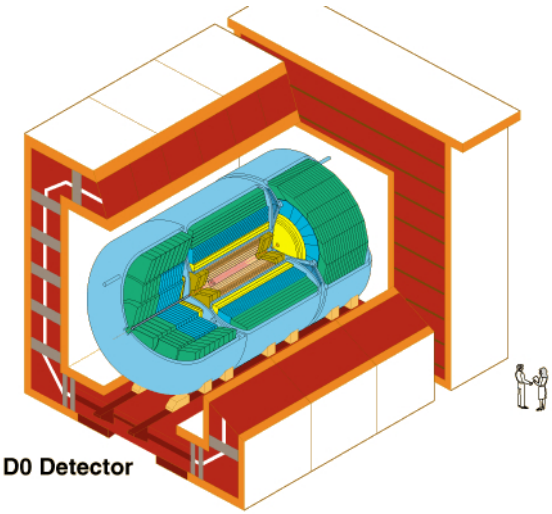
September 9, 2014

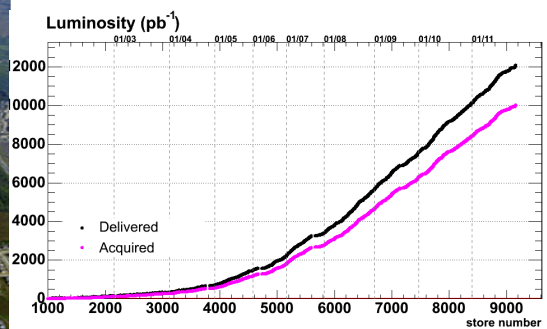
Introduction - Tevatron @ Fermilab

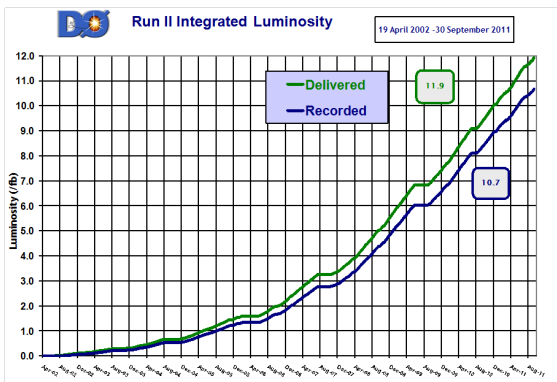
- $p - \bar{p}$ Collider with $\sqrt{s} = 1.96$ TeV
- Run II ended in Sep. 2011 $\mathcal{L}^{int} \approx 10$ fb^{-1} available for CDF and D0 experiments





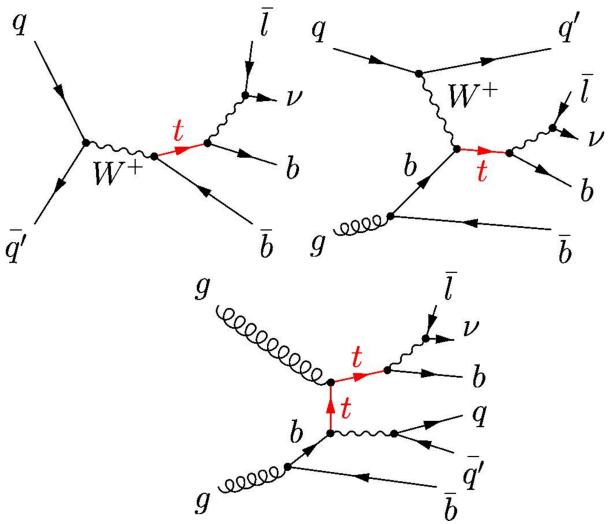


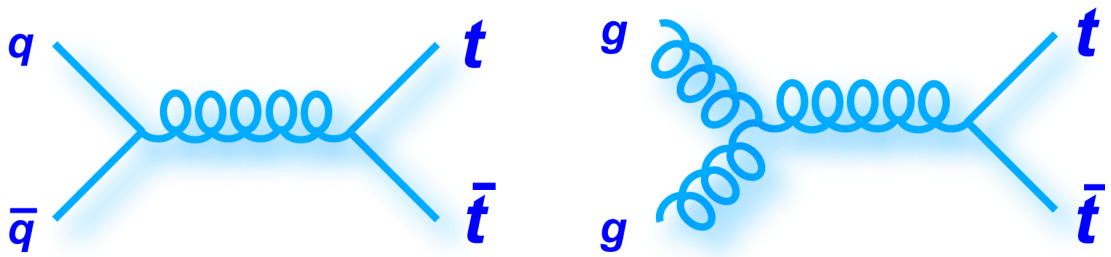




Introduction - Top Quark Production at Tevatron

- Top Quark (t) discovered at Tevatron in 1995
  PRL 74 2626, PRL 74 2632 (1995)
- QCD SM $\sigma^{SM}_{p\bar{p}\to t\bar{t}} = 7.35^{+0.28}_{-0.33}$ @ NNLO + NNLL for $m_t = 172.5$ GeV
  PRL 110, 252004 (2013)





Quark-Antiquark annihilation is dominant at Tevatron: 85% of total cross section

- EWK Single Top Production: first observed in 2009 (*PRL 103 092001, PRL 103 092002 (2009)*)
- $\sigma_{s-chan} = 1.06 \pm 0.06$ pb
- $\sigma_{t-chan} = 2.1 \pm 0.1$ pb
- $\sigma_{Wt-chan} = 0.22 \pm 0.08$ pb, too small to be isolated at Tevatron

PRD 83, 091503 (2011); PRD 81, 054028 (2010); PRD 82, 054018 (2010); arxiv:1210.7813 (2012)

Why study Single Top production?

- Allows direct measurement of the CKM matrix element $|V_{tb}|$
- $V_{tb}^{meas} = \sqrt{\sigma_{meas}/\sigma_{theory}}$ in SM $\sigma_{theory} \rightarrow |V_{tb}| = 1$

- Is it a 3x3 matrix? Why not a 4x3, 3x4, 4x4 or even larger?
- Is it unitary? $\rightarrow$ $|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$?
- First two rows in agreement with CKM unitarity from B meson decays precision measurements

Direct Measurements: see other talks

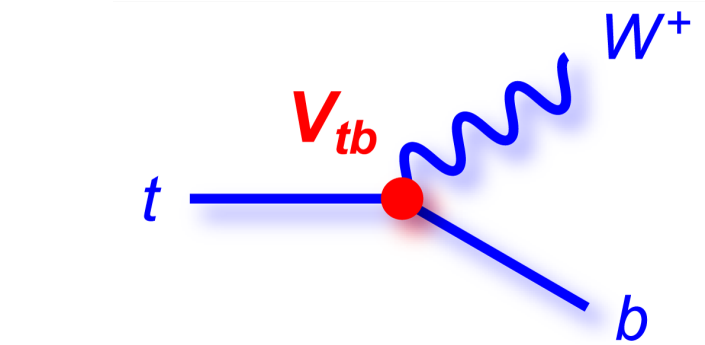
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

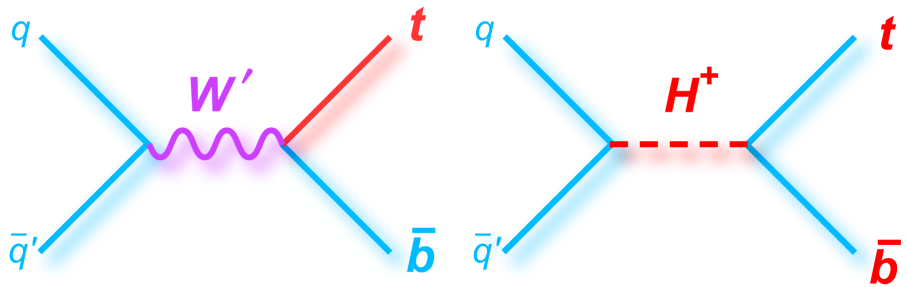
Ratio Constrained from Bs oscillations

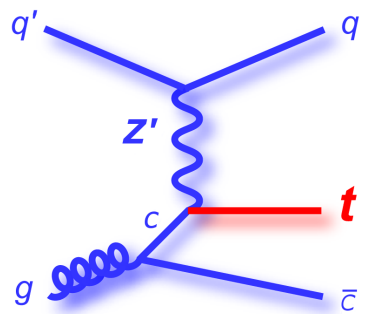
Measured under certain assumptions

Why study Single Top production? Not only for CKM!

- Test of Standard Model prediction
  - probe V-A coupling structure
  - Top quark spin access
- Target New Physics
  - Anomalous couplings
  - Presence of heavy charged bosons $W^{'}.H^{+}$ (s-channel)
  - Flavour Changing Neutral Currents (FCNC) through $Z^{'}$ (t-channel)

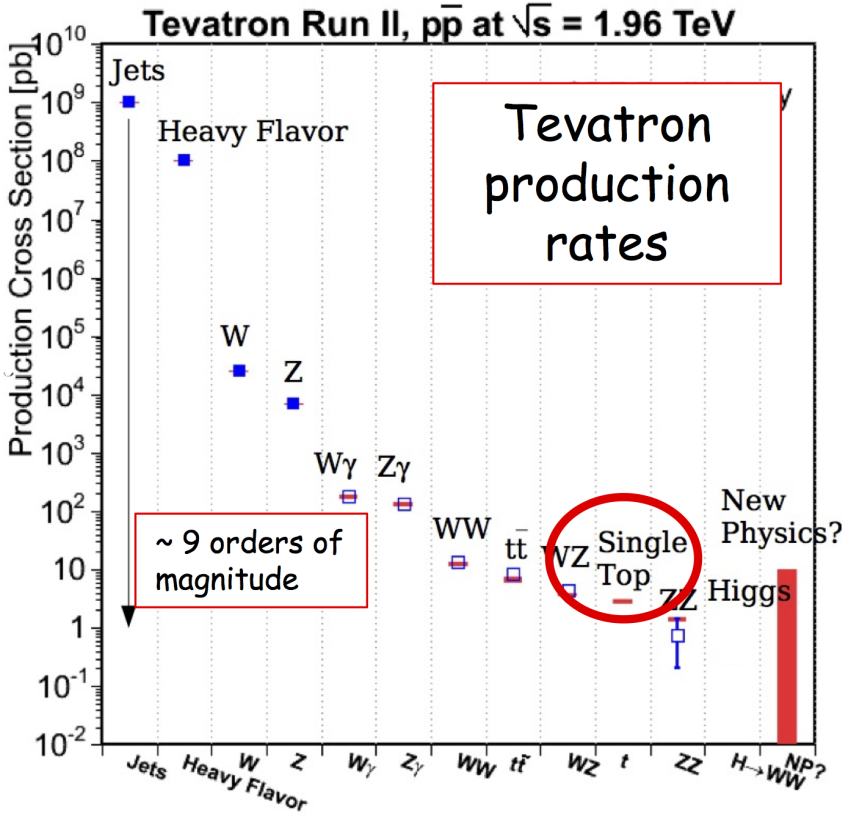


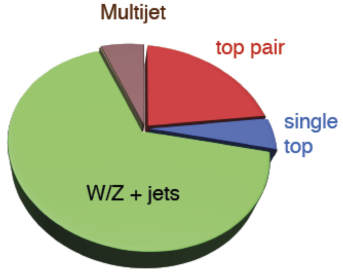


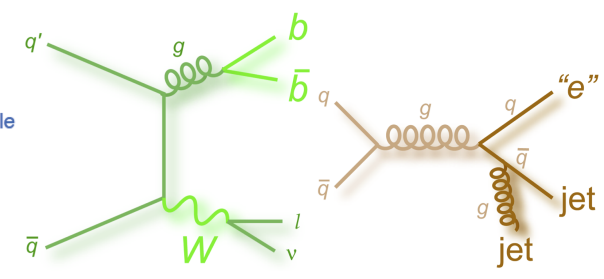


Single Top Tevatron Analysis - Outline

- Very rare process at Tevatron: $S/B \sim 1/10^9$
- Trigger: High-p_T lep $/\!\!\!\not{E}_T$ $\rightarrow S/B \sim 1/10^6$
- Topological event selection and b-jet identification: $\rightarrow S/B \sim 1/20$
- Very accurate background estimate is needed
- Major Backgrounds:
  - **W+Jets**: Shape from MC, Normalisation from Data
  - **Dibosons, Z+jets, $t\bar{t}$**: From Simulation
  - **Multijet**: Data driven shape and normalisation







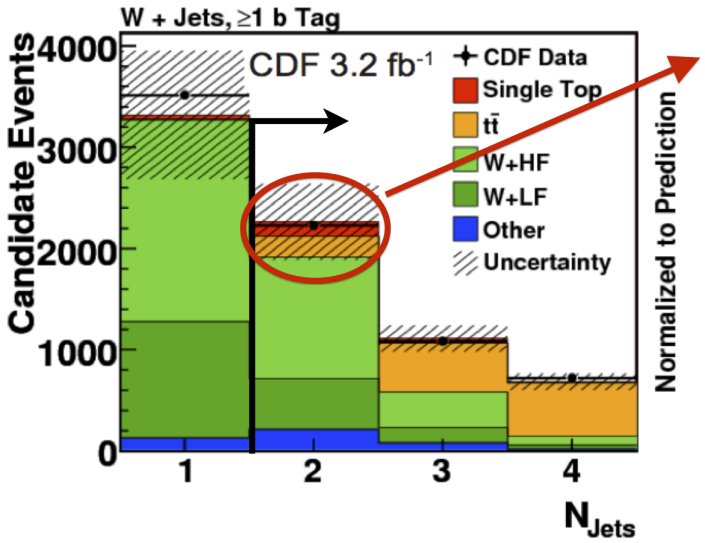
Single Top Tevatron Analysis - Outline

W+Jets Selection (D0 and CDF):

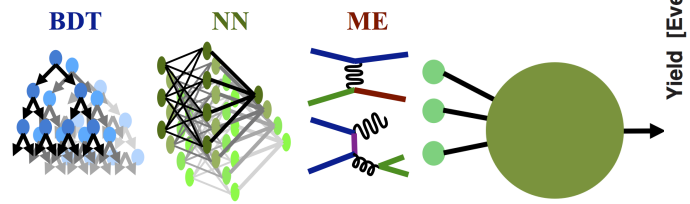
- One high-p_T isolated lepton (e/μ)
- Large $\not\!\!E_T$ from the ν
- 2 or 3 high-p_T jets, with at least one identified as *b-jet*

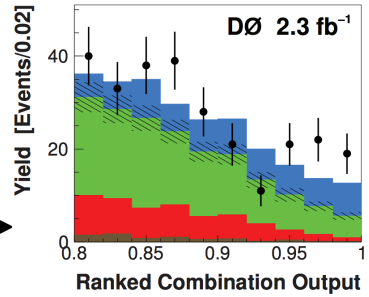
$\not\!\!E_T$+Jets Selection (CDF):

- High-$\not\!\!E_T$ and lepton veto
- 2 or 3 high-p_T jets, with at least one identified as *b-jet*
- Orthogonal to W+jets selection (+33% acceptance)



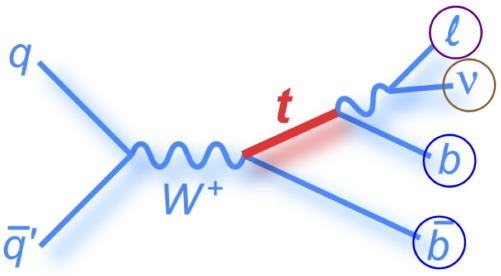
After topological selection the single top signal is hidden behind backgrounds with large uncertainties (up to 30% for W +HF normalisation) A counting experiment is not possible





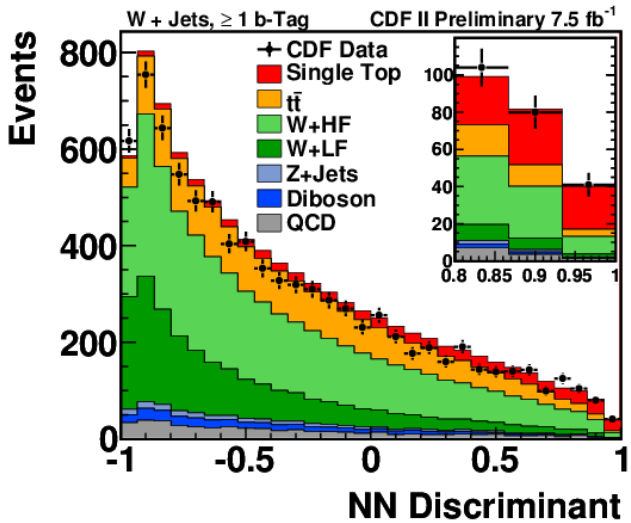
- Signal hidden behind large backgrounds with large uncertainties
- No single variable provides enough discriminating power to separate S from B
- Multivariate techniques are used, trained separately for s- and t-channel
- Cross section extracted from a binned likelihood fit on the combined discriminant

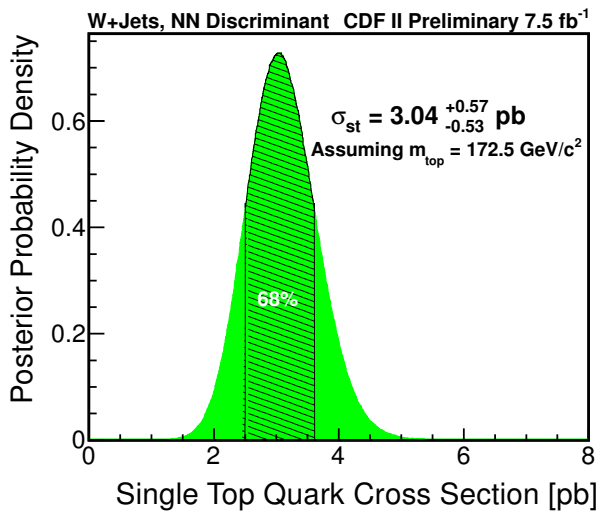
Single top s+t channel $l\nu b\bar{b}$ Final State



- Total Luminosity: 7.5 fb^{-1}
- 4 sub-channel according to N_{tags}/N_{jets}
- Samples with shifted systematics included in the artificial NN training $\rightarrow$ 3% resolution improvement
- Control region for background validation: 0 b-jet sample
- Binned Likelihood fit on the NN output. Bayesian posterior assuming non negative prior

$$\sigma_{st} = 3.04^{+0.57}_{-0.53}\ \text{pb}$$





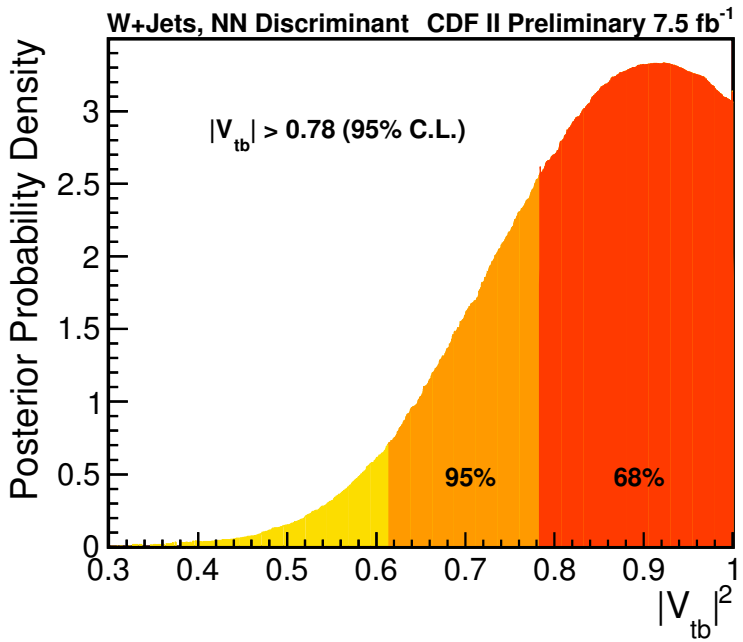
CDF pub. Note 10793
Submitted to PRL

Extraction of V_{tb} $l\nu b\bar{b}$ Final State

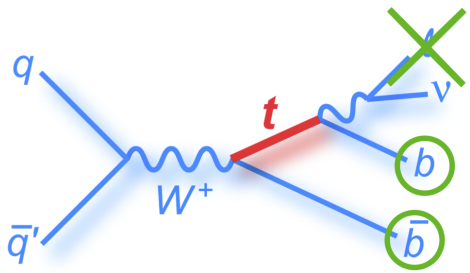
- Since $\sigma_{st} \propto |V_{tb}|^2 \rightarrow$ Flat prior within $0 \leq |V_{tb}|^2 \leq 1$, Bayesian posterior
- **SM Assumptions:**
  - CKM elements hierarchy: $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$
  - CP conserving and V-A nature of Wtb vertex
- No assumption on number of generations or unitarity
- Complementary with indirect $|V_{tb}|$ measurement (see later in the Talk!)

Results:

- $|V_{tb}| = 0.95 \pm 0.09$ (stat+syst) $\pm$ 0.05 (theo)
- $|V_{tb}| > 0.78(95\%)$ C.L.

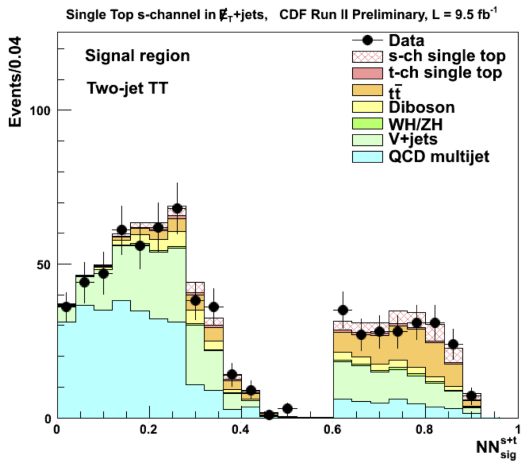


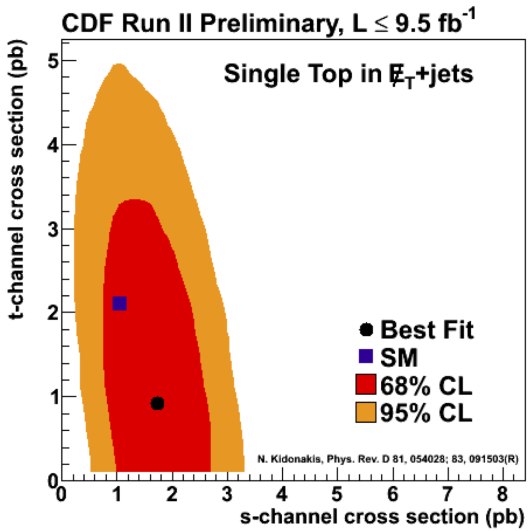
Single Top $\not{E}_T b\bar{b}$ s+t analysis



- Total Luminosity (9.5 fb$^-$1)
- Recovers events where the lepton are lost or $W \to \tau\nu_\tau$
- Use of new multivariate b-jet identification algorithm: HOBIT
- 1D MVA discriminant obtained from the combination of MVAs for s- and t-channel separately
- Serie of NNs used against QCD, V+jets and $t\bar{t}$ bkgs
- The total cross section is extracted assuming SM σ_s/σ_t

CDF pub. Note 11033





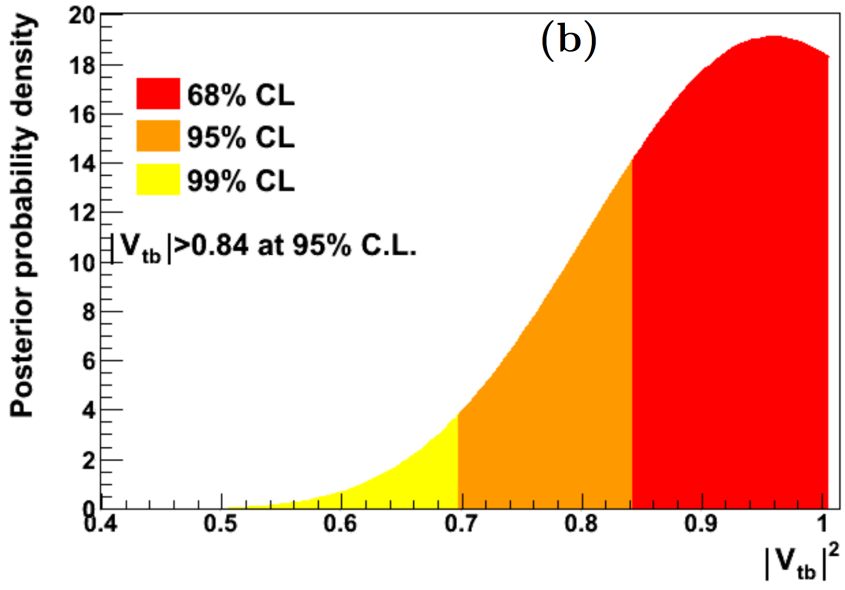
$\sigma_{s+t} = 3.53^{+1.25}_{-1.16}$ pb
$|V_{tb}| > 0.63$ at 95% C.L.

Single top s+t CDF combination

- The $l\nu b\bar{b}$ and $\not\!\!E_T b\bar{b}$ channels are statistically independent
- The two analyses shown have been combined for more accurate cross section measurement and stronger lower limit on $|V_{tb}|$

- The results are combined multiplying the Likelihood, simultaneously varying the correlated uncertainties.
- The combined measurement results in an $\sigma_{s+t} = 3.02^{0.49}_{-0.48}$ pb.

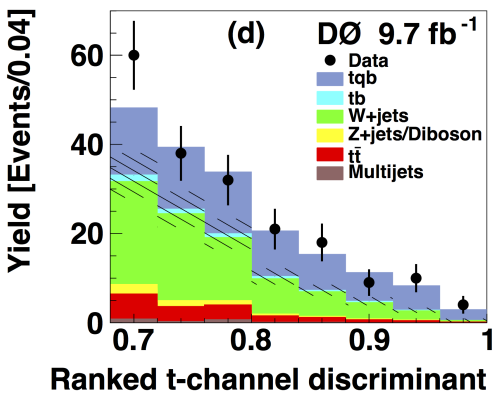
$|V_{tb}| > 0.84$ at 95% C.L

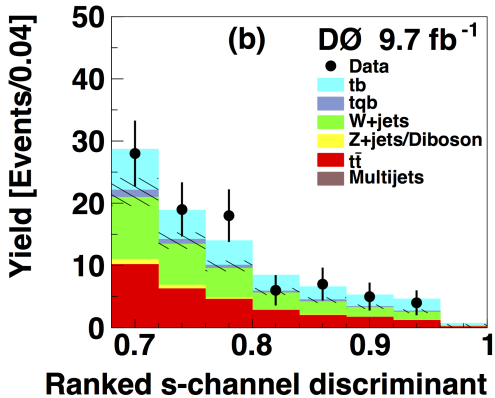


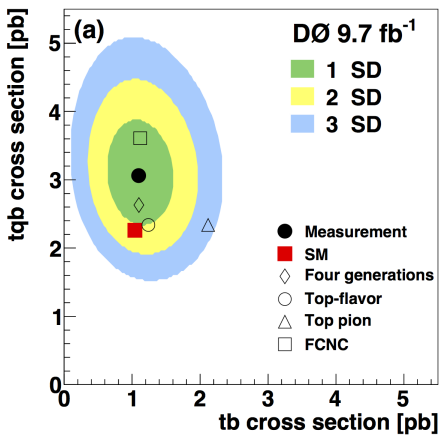
pub. Note 11033

Single top s+t channel $l\nu b\bar{b}$ Final State

- Total Luminosity: 9.7 fb^{-1}
- Possibility of an anomalous strength of the left-handed Wtb coupling (f_1^L)
- Three MVA with BDT, ME and BNN combined in a single discriminant through a BNN.
- Separate discriminants for s- and t-channel, D_s^{comb} and D_t^{comb} respectively. A 2D discriminant is then formed.
- Integration over σ_t (σ_s) and extract σ_s (σ_t)
- 2D posterior D_{s+t}^{comb} is then formed versus σ_t. Measurement of σ_{s+t} obtained integrating on σ_t. No assumption on σ_s/σ_t is made







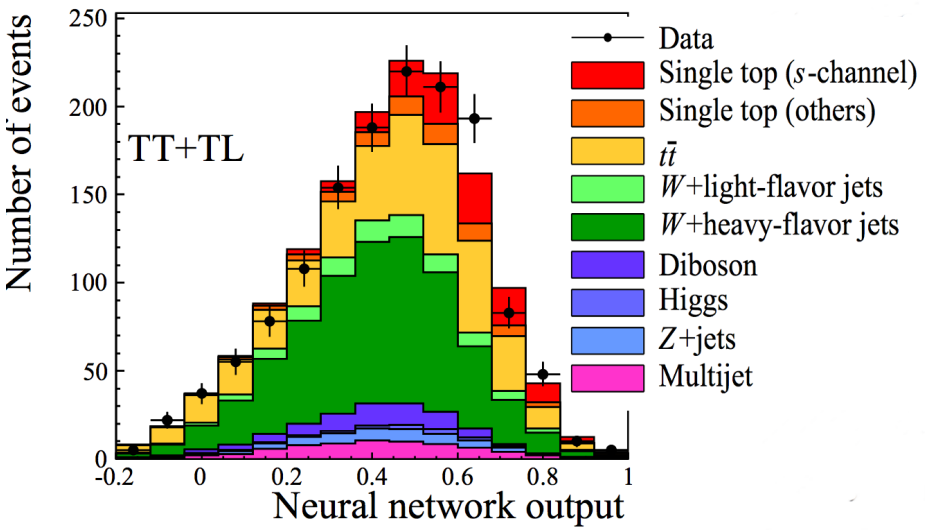
$$\sigma_s = 1.10^{+0.33}_{-0.31} \text{ pb}$$
$$\sigma_t = 3.07^{+0.53}_{-0.49} \text{ pb}$$
$$\sigma_{s+t} = 4.11^{+0.59}_{-0.55} \text{ pb}$$

$|V_{tb}f_1^L| = 1.12^{+0,09}_{-0.08}$ (stat+syst)
SM: $f_1^L = 1 \rightarrow |V_{tb}| > 0.92$ 95% C.L

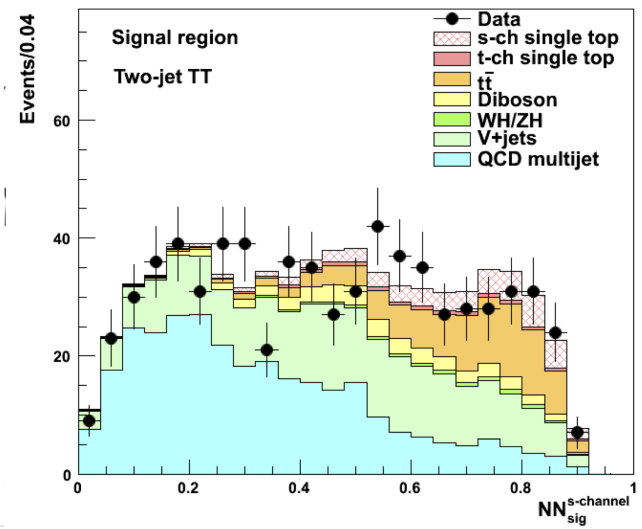
Phys. Lett. B 726, 656 (2013)

CDF s-channel optimised analyses

- Two new analyses for s-channel in l+jets and $\not\!\!E_T$+jets final state with 9.4 fb^{-1}
- Based on $H \to b\bar{b}$ searches techniques. Multivariate b-tagger HOBIT with tight (T) and loose (L) working points
- NN optimised for s-channel event topology. t-channel is part of the bkg, with normalisation from theory



PRL 112, 231804 (2014)



PRL 112, 231805 (2014)

$\sigma_s = 1.41^{+0.41}_{-0.42}$ (stat+syst) pb

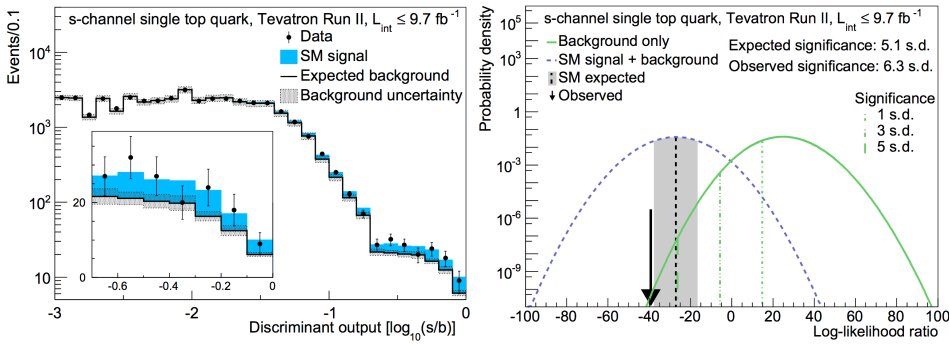
$\sigma_s = 1.12^{+0.61}_{-0.57}$ (stat+syst) pb

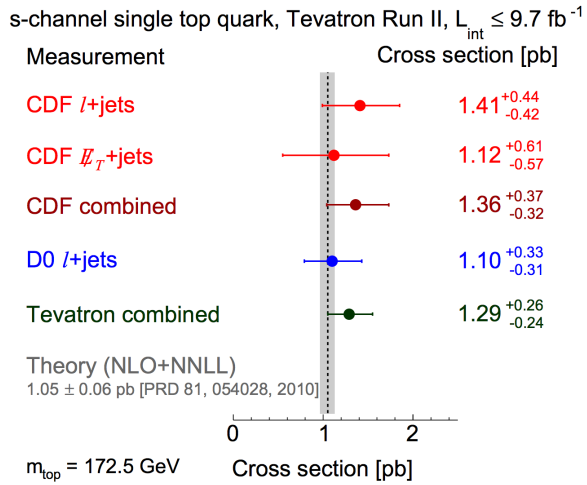
Tevatron s-channel combination

- The results of the CDF and D0 analyses on the s-channel have been combined
- First observation of s-channel single top (significance 6.3 standard deviations)
- Systematics common to both experiments are taken as 100% correlated, the others are treated as uncorrelated

Systematic uncertainty	CDF		D0		Corre-
	Norm	Dist	Norm	Dist	lated
Lumi from detector	4.5%		4.5%		No
Lumi from cross section	4.0%		4.0%		Yes
Signal modeling	2–10%	•	3–8%		Yes
Background (simulation)	2–12%	•	2–11%	•	Yes
Background (data)	15–40%	•	19–50%	•	No
Detector modeling	2–10%	•	1–5%	•	No
b-jet-tagging	10–30%		5–40%	•	No
JES	0–20%	•	0–40%	•	No

PRL 112 231803 (2014)





$$|V_{tb}| = 1.05 \pm 0.11$$

Indirect Measurements of V_{tb}

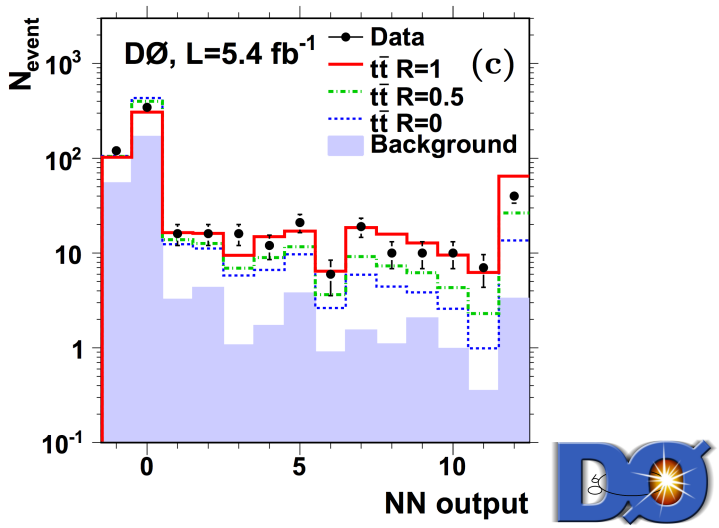
- The t quark decay rate through the production of a W boson and a down type quark $q = d, s, b$ is proportional to $|V_{tq}|$
- In the SM $t \to Wb$ $\approx$100% of the times
- Using top pairs event produced at Tevatron, it is possible to measure the actual ratio and an indirect measurement on V_{tb} can be extracted

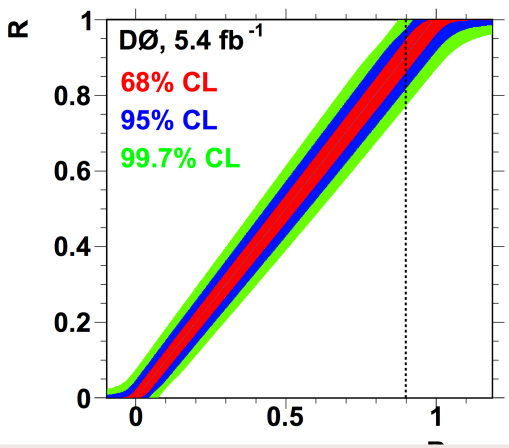
$$R = \frac{\mathcal{B}(t \to Wb)}{\mathcal{B}(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

- Under the assumption of a 3x3 unitary CKM $\to R = |V_{tb}^2|$

Indirect Measurements of V_{tb} - Lepton+Jets/Dilepton

- Total luminosity: 5.4 fb^{-1}
- Combination of High-p_T lep (e/μ) and jets and dileptonic final state
- Use of a NN b-tagger to identify jets originating from b-quarks.
- Additional MVA in l+Jets sample to discriminate S from B
- New MC are generated with final state $t\bar{t} \to WbWq$ and $t\bar{t} \to WqWq$.
- Binned likelihood fit on the subsamples and the b-tagger NN output. Simultaneous fit on the $\sigma_{p\bar{p}\to t\bar{t}}$
- FC prescription for limit extraction





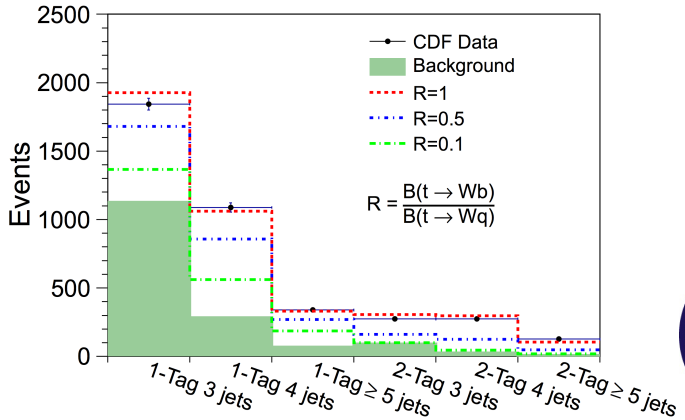
$|V_{tb}| = 0.95 \pm 0.02$

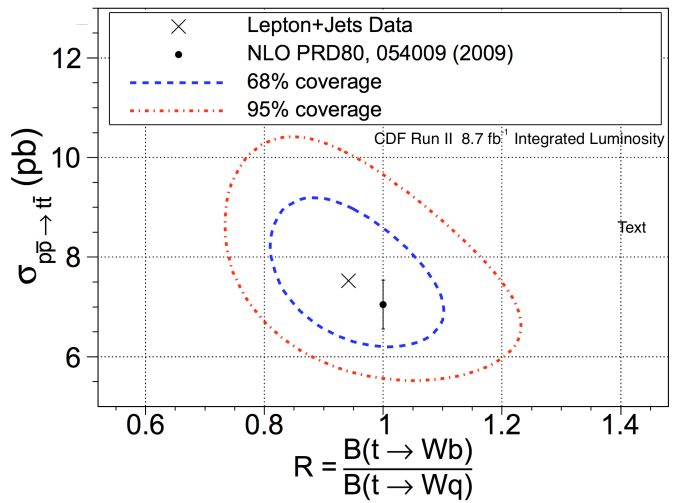
$|V_{tb}| > 0.96$ at 95% C.L

PRL 107, 121802 (2011)

Indirect measurements of V_{tb} - Lepton + Jets

- High-pT lepton (e/μ) and large $\not\!\!E_T$ sample
- Final state subdivided in channels according to number of jets/b-jets
- Counting experiment and simultaneous Likelihood fit on the observed events
- Simultaneous measurement of $\sigma_{p\bar{p}\to t\bar{t}}$. For $|V_{tb}|$ limits: prior flat in R within [0,1]
- Signal MC for $t\bar{t}$ is generated using $|V_{tb}| = 1$
  - Each jet originated from t and truth matched to b get assigned a probability $P_b < R$
  - Simulate a configuration where t decays in light flavour jet with probability $1 - R$ times



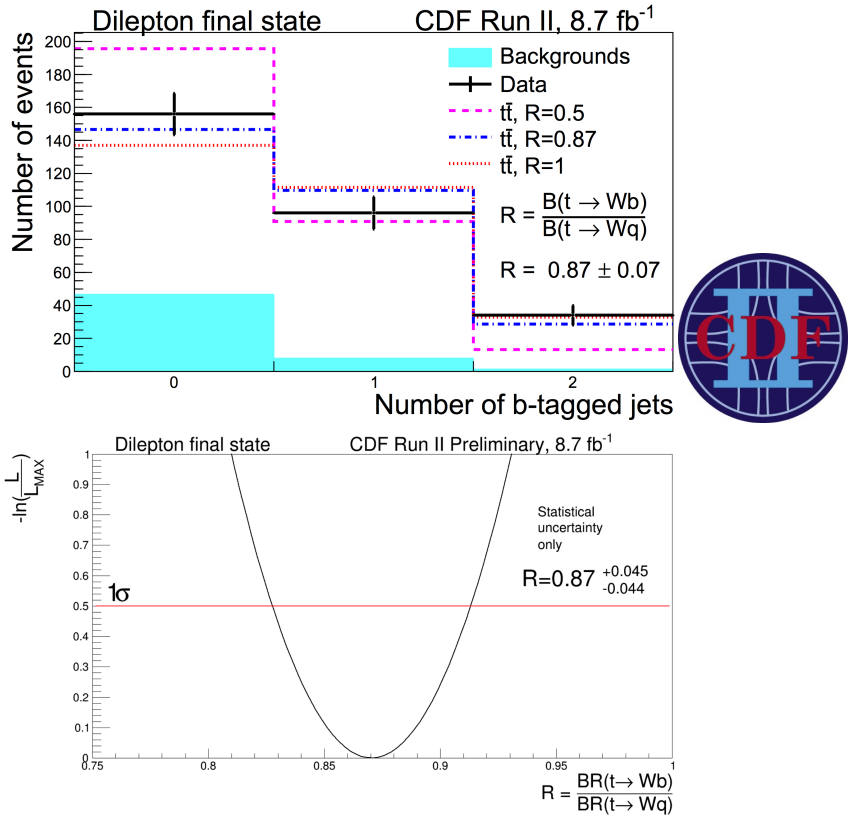


$V_{tb} = 0.97 \pm 0.05$ (stat+syst)
$V_{tb} > 0.89$ at 95% C.L.

PRD 87 111101(2013)

Indirect measurements of V_{tb} - Dilepton

- Dileptonic final state with large $\not\!\!E_T$
- High purity $t\bar{t}$ signal in selected sample $\rightarrow$ measurement $\sigma_{p\bar{p}\rightarrow t\bar{t}} = 7.64 \pm 0.55$ (stat) pb, free of $\mathcal{B}(t \rightarrow Wb)$ assumptions
- Measured $\sigma_{p\bar{p}\rightarrow t\bar{t}}$ is used to constraint the signal in the sub-channels $(ee), (e\mu), (\mu\mu)/N_{b-jets}$



$V_{tb} = 0.93 \pm 0.04$ (stat+syst)
$V_{tb} > 0.85$ at 95% C.L.

PRL 112 221801 (2014)

Summary and Conclusions

Summary

- t quark first observed by CDF and D0 in 1995. Single top in 2009
- During years, more refined measurements of top properties
- Direct and indirect measurements of V_{tb} have been presented
- CDF single top program is almost complete
- Combination of the CDF R measurement is under way.

Experiment	Type	$\|V_{tb}\|$	$\|V_{tb}\| >$ ... @ 95% C.L
CDF	Single top (s+t) l+jets	0.95 ± 0.10	0.78
CDF	Single top $\not\!\!E_T$+jets	-	0.63
CDF	Single top (s+t) combo	-	0.84
D0	Single top (s+t)	$1.12^{+0.09}_{-0.08}$	0.92
CDF+D0	Single top (s)	1.05 ± 0.11	-
CDF	$t\bar{t}$ l+jets	0.97 ± 0.05	0.89
CDF	$t\bar{t}$ ll	0.93 ± 0.04	0.85
D0	$t\bar{t}$ l+jets/ll	0.95 ± 0.02	0.96

BACKUP

New Physics extensions to CKM matrix

- Theoretically a 3x3 unitary CKM matrix leaves no room for low values of V_{tb}.

$$|V_{tb}| = 0.999138^{+0.000052}_{-0.000030}$$

- Lower values of $|V_{tb}|$ can be obtained with different BSM mechanisms
  - Presence of a single extra vector-like quark (t', b'), respectively up/down type (4x3,3x4 CKM matrix)
  - Presence of a full SU(2)xU(1) forth generation

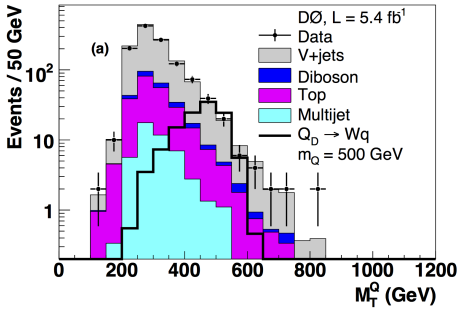
$$V'_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix}$$

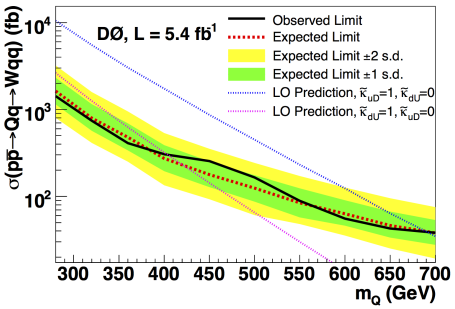
Eur. Phys. J. C49 791-801 (2007)

Last Tevatron limits on CKM extensions

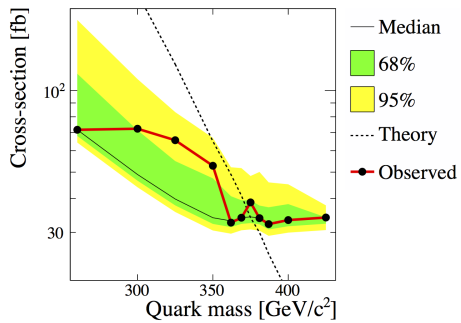
- Single Vector Like t' searches
  - l+jets at 5.4 fb^{-1}
  - Coupling $k_{qQ} = \frac{v}{m_Q}\tilde{k}_{qQ}$. Focusing on $t' \to Wq$
  - Discriminating variable: M_T^Q
- Chiral b' 4th Gen. searches
  - Analysis in l+$\geq$ 5 jets ($\geq$ 1b) at 4.8 fb^{-1}
  - Analysis for $b' \to Wt$
  - Discriminating variable: $S_T^{N_{jet}} = \sum_{jets} p_T^i + p_T^{lep} + \not{E}_T + X(N_{jet})$
- Chiral t' 4th Gen. searches
  - $m(b') + m(W) > m(t')$
  - Analysis for both $t' \to Wq$ and $t' \to Wb$ at 5.6 fb^{-1}
  - 2D binned likelihood fit on H_T and M_{reco}

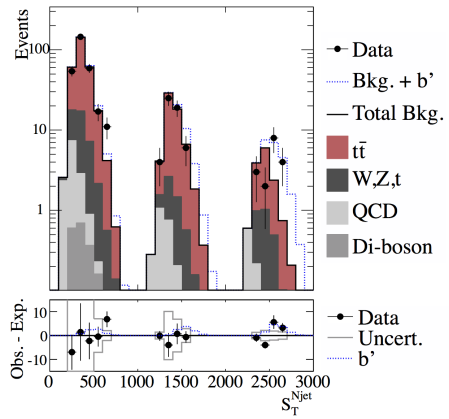
PRL 106 081801 (2011)



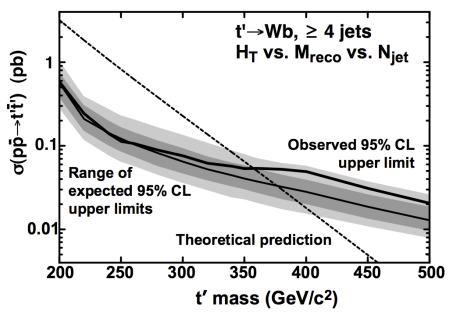


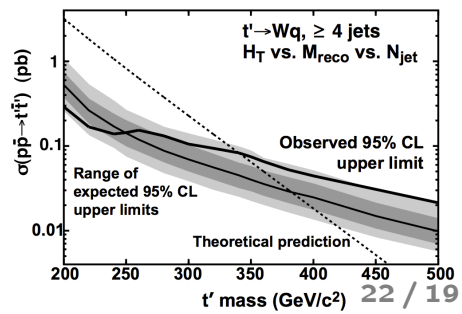
PRL 106 141803 (2011)



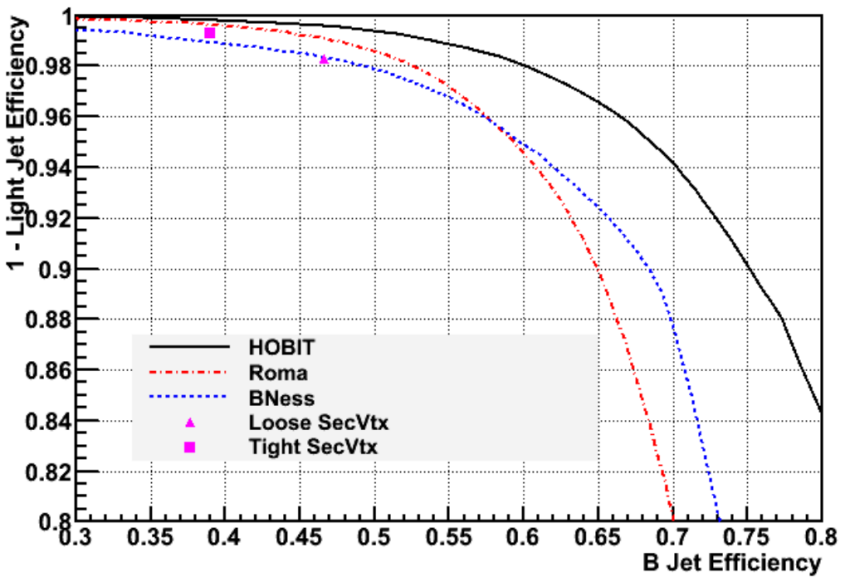


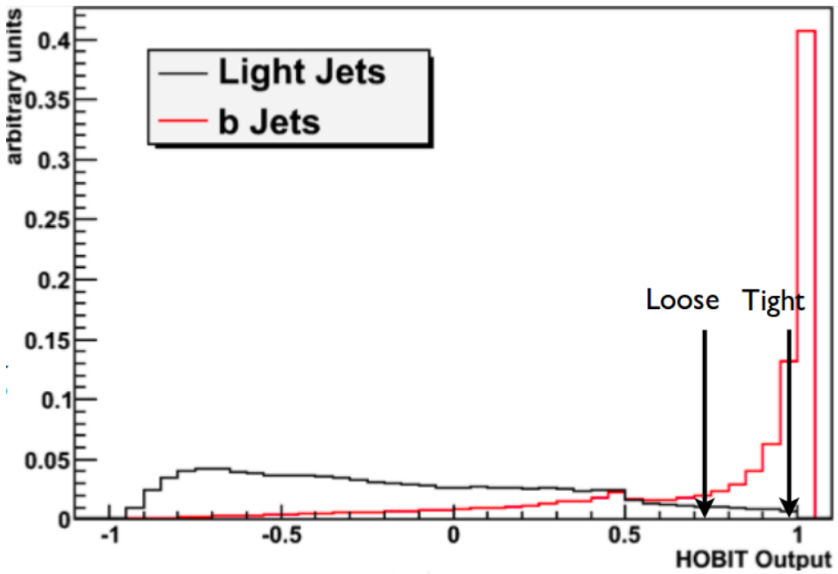
PRL 107 261801 (2011)





HOBIT - Slide Courtesy of M.Cremonesi (Moriond QCD - March 2014)

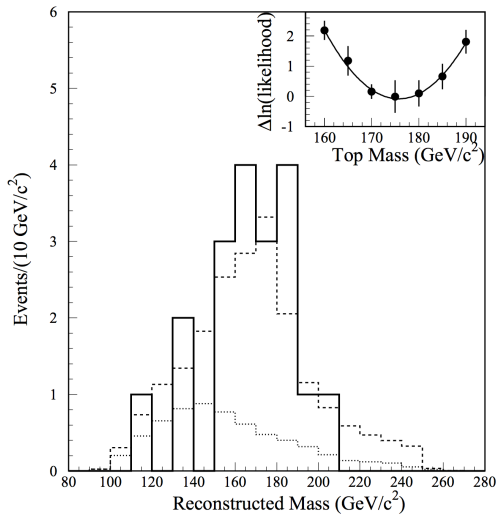


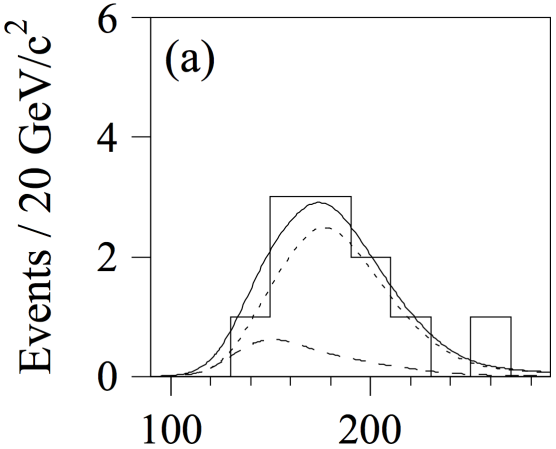


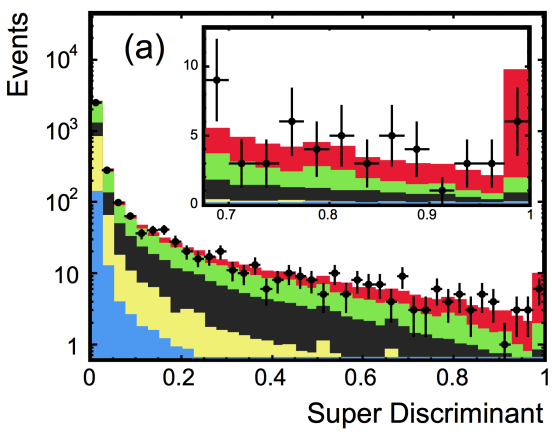
- A new b-jet identification algorithm optimized for $H \to b\bar{b}$ searches is employed: HOBIT
- Incorporates all the features of the previous CDF b-taggers
- Two different HOBIT cuts are used: tight b-tag (T) and loose b-tag (L)

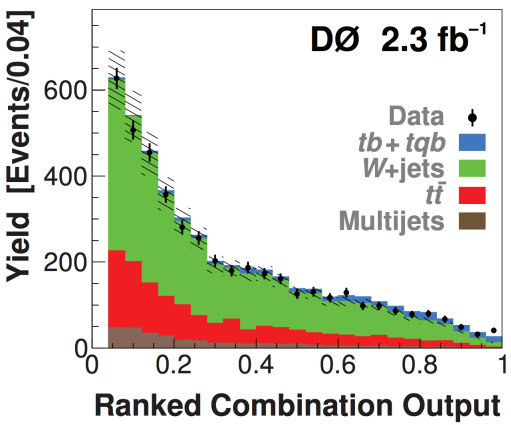
Introduction - Top Quark Discovery

- Top-Quark (t) has been discovered through strong interaction at Tevatron in 1995. (PRL 74 2626 (1995) , PRL 74 2632 (1995))
  - CDF: Likelihood Fit on the M_t
  - D0: Background only fit on the H_T and fit on M_t
- In 2009 single-top production via electroweak interaction has been discovered by CDF and D0 experiments
- Cross section measurement obtained from a binned likelihood fit on a Neural Network (NN) discriminant









Introduction - Top Quark

- Top Quark Discovery (D0):
  $H_T = \sum E_T^{jets}$ In the single lepton or $\mu\mu$ channel
  $H_T = E_T^{leading-e} + \sum E_T^{jets}$ in the $e\mu$ and ee channels